

Mesoscale Processes In Tropical Cyclones

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LONG-TERM GOALS

Our long-term goals are to develop improved understanding and prediction of the atmosphere, with particular emphasis on tropical cyclones. Our work encompasses research into basic processes, observing system development and related field programs, and development of forecast and impacts reduction systems.

OBJECTIVES

To investigate the impact of mesoscale processes on the motion and development of tropical cyclones by theoretical and modeling studies and by the gathering and diagnosis of data. The appropriate research findings are directed towards strategic development of methods and approaches suitable for transition to operational use.

APPROACH

We have adopted a stratified research approach, including use of quasi-analytic methods to provide hypotheses and indications of the potential processes, followed by application to sophisticated numerical experiments and diagnostic examination of actual tropical cyclones. We aim to support direct operational implementation of our findings.

WORK COMPLETED

We have made substantial progress on documenting and understanding several aspects of tropical cyclone motion and development during this research program. Work completed in previous years includes: a comprehensive analysis of the manner in which atmospheric vortices can interact; the first research results on the presence of mesoscale vortices in tropical cyclones and their effect on motion and development; an explanation for the tendency of cyclones to meander about a mean path; a comprehensive analysis of the manner in which a cyclone interacts with the larger-scale circulations to influence tropical cyclone formation and initial development; analysis of the

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baroclinic effects on tropical cyclone motion; thermodynamic estimation of tropical cyclone intensity, which has been utilized in a WMO statement on climate change and tropical cyclones; the first assessments of the effects of spray on tropical cyclones and examination of boundary-layer processes on tropical cyclone structure and development; an analysis of the predictability of tropical cyclone tracks; the Global Guide to Tropical Cyclone Forecasting; and several forecasting techniques.

During 1999 we have completed three major programs:

We have led the successful international effort to establish an ***International Tropical Cyclone Landfall Program*** under the auspices of the World Weather Research Program and the Tropical Meteorology Research Program of the World Meteorological Organization. This program will work closely with the USWRP on landfalling tropical cyclones. The focus is on wind fields and rainfall. The windfield component has been identified as of prime importance to Navy requirements and includes continued work on track, intensity and structure changes.

Several upgrades have been made to the ***Northwest Cape Boundary-Layer Observing Site***. We have implemented new procedures to remove a software bug that was detected in 1998; we have also developed a new in situ system for logging the sonic anemometers, which will be less reliant on radio modem communications and therefore considerably more reliable.

We have completed our ***Tropical Cyclone Model (TCM3)*** and made it available to the community. Very high resolution (5km) is achieved in the cyclone core region by triply nested movable mesh algorithm. The turbulence mixing is accomplished by a turbulence kinetic energy (TKE) closure scheme in which both TKE and its dissipation rate are prognostics. The cloud microphysics are explicitly simulated by a bulk parameterization scheme in which mixing ratios of water vapor, cloud water, rain water, cloud ice, snow and graupel are all prognostics. Our numerical results have shown that the model can be used as a powerful tool for studying many aspects of tropical cyclones, especially, the core dynamics, rain bands, intensity and intensity change.

RESULTS

During 1999 our research efforts were focused on the mechanisms that limit tropical cyclone intensity; the boundary-layer structure under high wind conditions; the impact of sea spray on cyclone intensity; and predictability of tropical cyclone tracks.

Limitations on tropical cyclone intensity: Thermodynamic techniques derived by Emanuel (1991) and Holland (1997) provide an excellent estimate of the maximum potential intensity (MPI) that can be achieved in a given environment. However, the maximum intensity reached by tropical cyclones in all ocean basins are generally less than that which would be inferred from thermodynamic techniques applied to climatological data (DeMaria and Kaplan 1995, Evans 1993).

Why do so few cyclones reach their maximum potential intensity? What is it that limits tropical cyclone intensification? Our analysis indicates that a remarkably wide variety of processes work to inhibit cyclone intensification to its maximum potential intensity. In addition to the well-established sensitivity to local changes in the oceanic state, we have found significant sensitivity to the details of thermodynamic and vertical structure of the atmospheric environment, the cyclone motion, the presence of land (even at relatively large distances) and the microphysical processes in the model clouds.

There has been little direct analysis of the impacts of cloud physics on cyclone intensification. Much of the available work relates to forecast rules relating the observed effects of external processes on the convective structure (e.g. Merrill 1993). Whilst the cyclone could not exist without moist convection, we have found that some cloud processes also provide an inhibition to intensification. An example is provided in Fig. 1, which shows the effects of changing the cloud characteristics in a tropical cyclone simulation with our TCM3 model on an f-plane, with an environment specified by the January mean conditions in the Coral Sea.

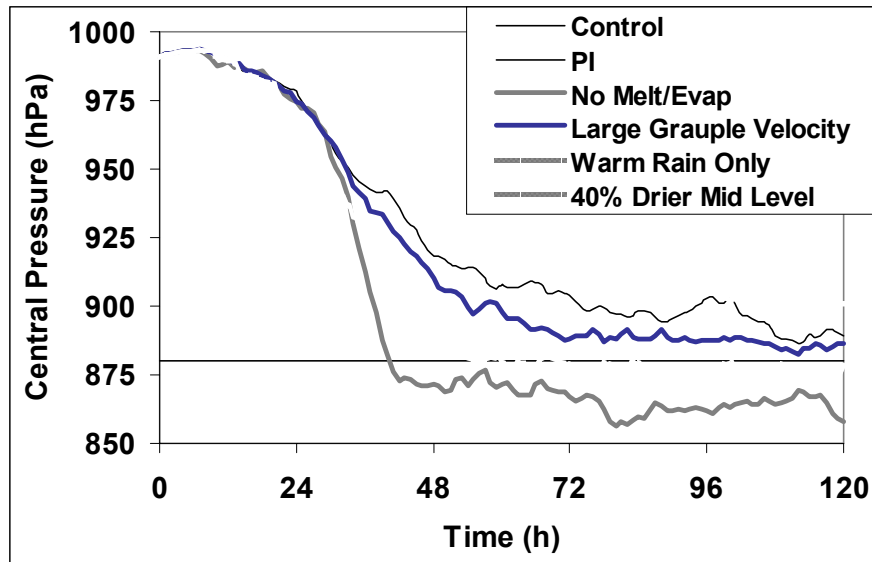


Figure 1. Intensity variations in a simulated tropical cyclone arising from changes to cloud processes. The control is on an f-plane with a thermodynamic environment defined by the January conditions in the Coral Sea. The thin horizontal line indicates the maximum potential intensity for these conditions.

We see that using a parameterization for warm rain only (which is common in operational numerical models) produces a cyclone that is significantly more intense than the both the control and the local thermodynamic limit. A similar result applies when melting and evaporation is removed. The inhibition to cyclone intensification in the control case arises from downdrafts generated by the clouds that spread low energy air throughout the boundary layer and inhibit the cyclone development. This is emphasized by the experiment in which we arbitrarily reduce the mid-level humidity of the environment by 40%, thus enhancing downdraft development and further inhibiting the simulated cyclone intensification. Interestingly, early forecast rules (e.g. McRae 1956) described the inhibition on cyclone intensity that occurs when a tongue of dry air is advected into the cyclone core region.

Increasing the fall speed of graupel (within the normally accepted limits) also produces a significant intensification of the simulated cyclone. This occurs by the resultant limitation on stratiform cloud decks in the mid-upper levels.

Boundary-layer flow under high wind conditions: A major new work has been completed during the year on the development of a linear analytic model of the flow in the boundary layer of a moving tropical cyclone. We have shown that the boundary layer flow can be largely understood as the superposition of three components: a symmetric one due to the cyclone itself, and two wave number one components due to the interaction of the cyclone with the underlying surface. The symmetric component has a depth that decreases from one to two kilometers in the periphery to several hundred meters in the core. The two asymmetric components have distinct depth and

amplitude scales, with one being shallower and much weaker than the symmetric component, and the other one being several times deeper in the core, and of comparable strength.

We have previously carried out very high-resolution simulations of the tropical cyclone boundary layer, using a version of TCM3 forced by a parametric pressure field imposed at the upper boundary of 2 km. The predictions from the analytic model were compared with simulations from this latter model, with generally good agreement. It is straightforward to derive expressions from the analytic model for a range of meteorologically interesting and operationally significant parameters, including boundary layer depth, height of the low level jet, vertical motion, and near-surface wind speed, including the wave-number one asymmetry in each of these. As these agree well with the numerical model simulations, we expect that they will have considerable utility. Some differences between the models were also noted, the most significant being an under-prediction of the jet strength by the analytic model and some detail differences in the eye wall. These were shown to be due to the neglect of vertical advection and other nonlinear processes.

Impact of sea spray evaporation on tropical cyclone intensification and intensity: The explicit sea spray droplet evaporation and transport model that has been developed over the past few years was used to develop an understanding of how spray evaporation modifies the boundary layer, and to quantify the processes that limit the evaporation. An important negative feedback arises from the reduced evaporation rate from both the sea surface and the droplets due to increased humidity as spray is introduced. Feedbacks due to stability changes were shown to be less important than this. We found also that the evaporation layer was several tens of meters deep, for droplets near the peak production radius, and that these also have a residence time much longer than would be expected from their fall velocity alone. We consider that the proper inclusion of this effect is essential for accurate parameterization of spray-mediated thermodynamic fluxes and we have commenced work to re-evaluate existing observations in light of these findings.

Related numerical simulations using TCM3 have shown that invoking the Fairall et al (1995) spray parameterization does not significantly affect the potential maximum intensity of a tropical cyclone, but it does either increase or decrease the intensification rate of a model tropical cyclone depending on the use of different model microphysics parameterization schemes. Use of a full mixed-ice phase scheme reduces the intensification rate whilst a simple warm-rain processes only scheme increases the intensification rate. The former results from the generation of downdrafts outside of the cyclone core, while the latter is due to quick response of warm cloud processes to the boundary layer forcing. At the mature stage, the cyclones with and without the effect of sea spray have similar intensity because at this stage the boundary layer under the cyclone eye wall is nearly saturated and the effect of sea spray evaporation becomes less important.

Tropical cyclone predictability: Continuation of this program has resulted in an analysis of the degree to which current NWP models are approaching the best estimate of the limit of predictability for tropical cyclones as systems governed by a set of deterministically chaotic equations. The chaotic nature of the systems and the governing equations results from the inherent non-linearity together with the multifarious feedback processes that take place in such complex systems.

Table 1 summarizes our findings from three cyclone basins (Atlantic, NW Pacific and Australian region) using four years of best track archived data for the period 1994-1997. The first row is the estimate of the lower limit of predictability obtained using non-linear systems analysis applied to the data (Inherent 1). The second row is the corresponding estimate obtained using a Monte Carlo generated ensemble NWP procedure (Inherent 2). The interesting feature, observed in all the previous studies is how close the estimates are from these two very different approaches. These are compared to application of the combination technique of Fraedrich and Leslie (1988) to track

forecasts from the UNSW, UKMO and NCEP models (row 3 of table 1), which indicates a significant reduction in track forecast errors. It is noted that this approach, referred to as Inherent 3 should be applied rigorously and simple averages might yield short-term gains but have no genuine mathematical basis. It is hoped to add the NRL model NOGAPS to the list of models employed in the combination next year.

The major finding is that there is still a potential improvement of 35 to 50% between current best-forecast results and the predictability limit.

Table 1: Inherent error limits (km) for the three methodologies. These are compared with the errors currently being obtained in practice as shown on the bottom row.

	0 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
Inherent 1	0	39	79	96	135	169	213
Inherent 2	37	53	85	102	141	177	224
Inherent 3	27	45	66	92	123	142	191
Current	52	84	121	157	219	264	322

IMPACT/APPLICATIONS

Our strategic research is aimed at improved understanding and improved predictability of the intensity and movement of tropical cyclones. To ensure good feedback with operational staff, we maintain a regular program of seminars and discussions at major operational centers and meetings. The ONR program has had considerable direct and indirect impacts on the international science and operations through its high profile amongst various WMO forums, including the meetings of the WMO Tropical Cyclone Program and the International Workshops on Tropical Cyclones. The new initiative on tropical cyclone landfall will continue this interaction. As part of this effort we lead the publication of the Global Guide to Tropical Cyclone Forecasting (Holland et al., 1993)

TRANSITIONS

The group is interacting closely with a number of groups in the United States and internationally, including the Universities of Hawaii and Rhode Island, NASA Goddard, and the NOAA/AOML Hurricane Research Division.

The TCM3 also has been installed at the Universities of Hawaii and Rhode Island, to support their research on tropical cyclones. Our explicit cloud microphysics scheme has been implemented into the HIRES model at the University of New South Wales University and the LAPS model at BMRC. The MPI technique has been used for a statement on climate change by the World Meteorological Organization (Henderson-Sellers et al, 1997) and for a direct comparison to numerical modeling studies of climate change by the NOAA GFDL. We have prepared an extensive set of fields based on the NCEP reanalysis for research project by Chris Velden at Wisconsin.

RELATED PROJECTS

The Aerosonde Development Program (see separate report) will move to tropical cyclone missions next year, with provision of data for continuing our research activities. The WMO International Tropical Cyclone Landfall Program is geared to provide an international focus on the tropical cyclone boundary layer, track and intensity changes with an emphasis on processes relevant to landfall.

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